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# MuCOOL Facility Shielding Assessment

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Edited by M. Gerardi

## The MuCOOL Beamline and Experimental Hall

### *Description of Facility*

The MuCOOL Beamline extracts, transports, and delivers 400-MeV  $H^-$  beam directly from the Linac and Linac enclosure to a test facility, the MuCOOL Test Area (MTA) experimental hall. This experimental facility, located southwest of Wilson Hall, between the Linac berm and parking lot, will be used initially to support the MuCOOL R&D program and is designed to accept the full Linac beam pulse. The design concept for the MuCOOL facility is taken from an earlier proposal [1], but modifications were necessary to accommodate high-intensity Linac beam, cryogenics, and the increased scale of the cooling experiments. The MTA is one of the few such facilities in the world where a primary beam is available for experiments.

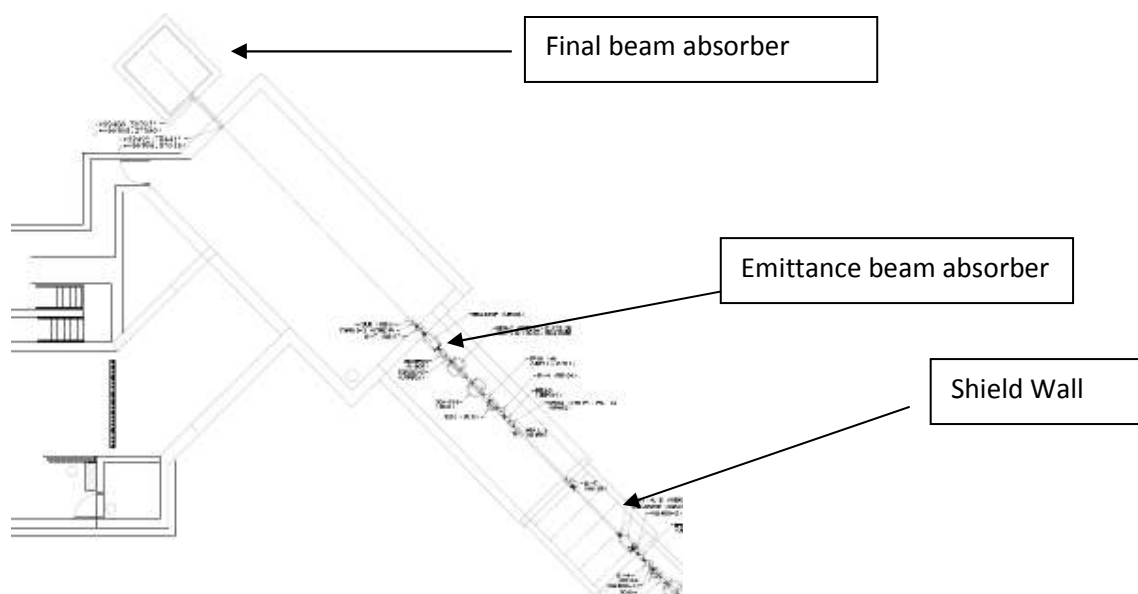
Most of the upstream MuCOOL beamline is housed in an enclosure contiguous with the Linac. The remaining downstream section of the beamline resides in a 30' beamline "stub" that opens into the experimental hall. A shield wall, located beneath the access hatch, separates the upstream section of the beamline from the downstream beamline stub and experimental hall. This wall effectively isolates the Linac primary beam enclosure from all downstream enclosures, preventing personnel access and exposure to radiation from Linac operation. Upstream of the shield wall, the beamline is installed in a pre-existing section of the Linac enclosure and on an inclined ramp which raises the beamline from the Linac elevation to the elevation of the stub. The layout of the beamline starting from the extraction point in the Linac up to the entrance of the experimental hall is given in Figure 1.

The facility will support two modes of operation. One mode is delivering beam to experiments. In addition, the beamline design incorporates a specialized insertion for beam diagnostics. This specialized insertion allows another mode of operation, or beamline tune, to be established which will provide detailed measurements of Linac beam properties such as emittance, greatly enhancing the functionality of this line, and supplying valuable information about accelerator operation. The two modes of operation are: 600 pulses/hour for an emittance measurement and 60 pulses/hour to the experiments. These modes will be referred to as the Emittance mode and Experiment mode, respectively. Two critical devices upstream of the shield wall, a 4-magnet dipole bend string, UHB03 (to

give its control system name), and a beamstop, UBS1, service both modes, as described in the MuCOOL Critical Device Justification.

## Assessment Boundaries

The boundary of the radiological area covered by this assessment starts at extraction from the Linac, which begins in the first pulsed C magnet (UHB01A) just upstream of the 400-MeV Chopper. (The 2<sup>nd</sup> C magnet, which completes the extraction process, is downstream of the Chopper.) Stationing begins at the upstream face of the first pulsed C magnet, defined as station Z=0. The endpoint of the assessment is defined by the mode of operation. For the Emittance mode, described below, the assessment endpoint is the emittance beam absorber; for the Experiment mode it is the final high-intensity beam absorber, which is buried in berm downstream of the experimental hall. Final absorber details are given in Figure 2 and in Attachment 4.



**SECTION A-A**

**SECTION B-B**

**LEGEND**

SYMBOL	DESCRIPTION	REFERENCE
1	Target	FIGURE 1
2	Backing	FIGURE 1
3	Support Structure	FIGURE 1
4	Target Assembly	FIGURE 1
5	Target Assembly	FIGURE 1
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98	Target Assembly	FIGURE 1
99	Target Assembly	FIGURE 1
100	Target Assembly	FIGURE 1

Figure 2. The downstream end of the MTA experimental hall, 6' section of buried beam pipe and beam absorber.

## ***Assessment Beam Parameters***

Two modes of operation will be supported in the MuCOOL beamline: one mode for emittance measurements (and beamline studies) and a second mode for MTA experiments. Maximum beam intensity for these two modes is given below.

### **Emittance Mode:**

- 1)  $9.6 \times 10^{15}$  protons/hr – 600 beam pulses/hour of full Linac beam pulse intensity ( $1.6 \times 10^{13}$  protons/pulse) to the emittance beam absorber (see Figure 1)

### **Experiment Mode:**

- 2)  $9.6 \times 10^{14}$  protons/hour – 60 pulse beam pulses/hour of full Linac beam pulse intensity to experiments in the MTA experimental hall.

In the Emittance mode, beam is always deposited in the emittance beam absorber. In the Experiment mode, three configurations are supported as follows and depicted in Figure 3.

- a) Beam is cleanly transported to the final high-intensity beam absorber through vacuum as shown in Figure 3 (top, left).
- b) Beam is transported to the final beam absorber with minimal interaction in experimental apparatus. Downstream components, including quadrupoles, collimators, and steering magnets, are required to transport to and deposit beam cleanly in the final absorber. An example of such a configuration is shown in Figure 3 (top, right).
- c) Beam is fully absorbed by the experimental apparatus and the final beam absorber is not used. No downstream magnetic components are required for this configuration as in Figure 3 (bottom).

All modes and all configurations will be handled operationally through Beam Permits and Running Conditions.

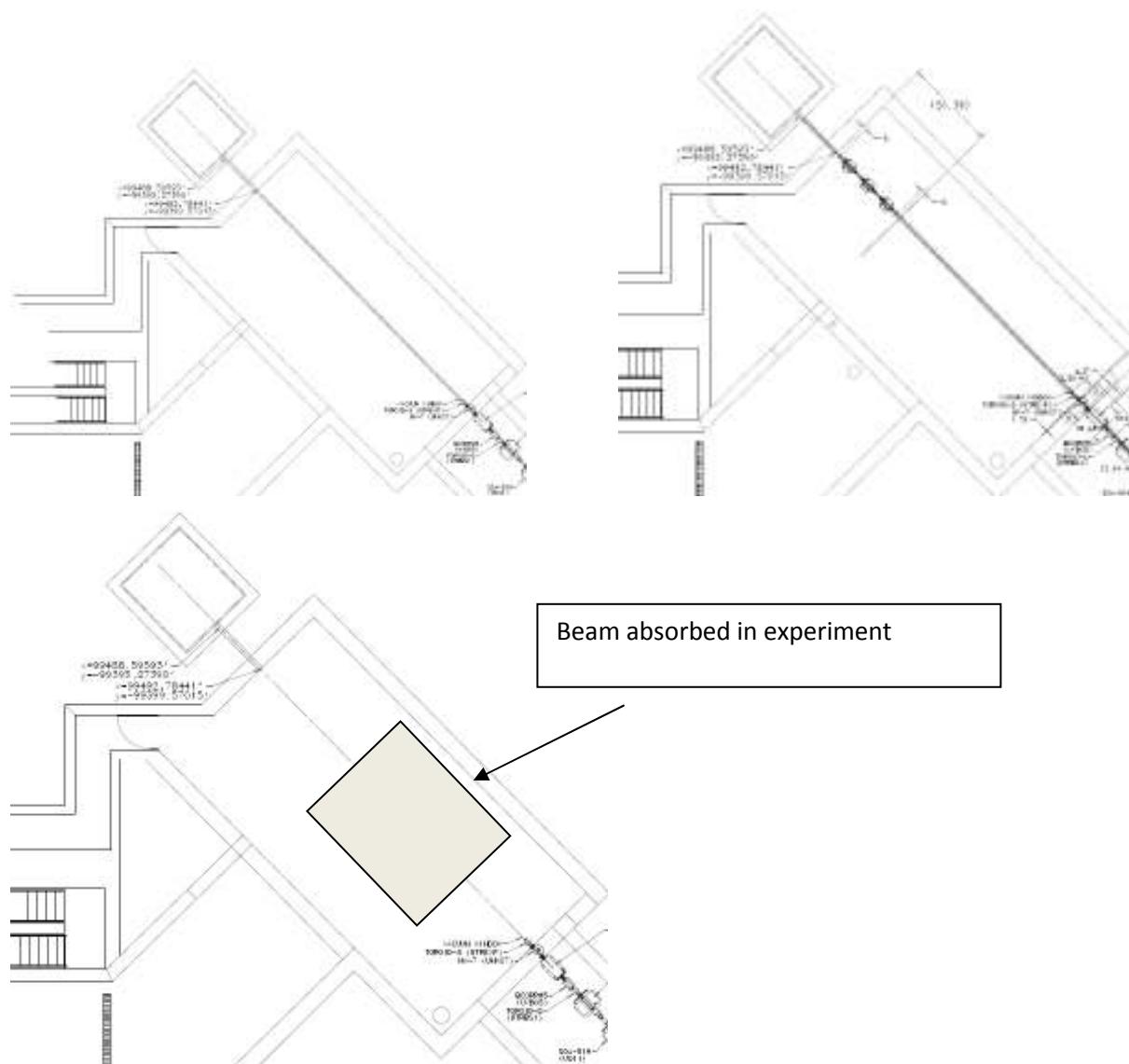


Figure 3. The experimental hall showing Experiment mode configuration a (top, left), b (top, right) and c (bottom).

## ***Shielding Requirements***

Attachment 1 contains the shielding requirements tables for the Emittance and Experiment modes described above.

## ***EMITTANCE MODE***

### ***Longitudinal Shielding Summary***

The longitudinal shielding part of the Emittance-mode assessment crosses six areas described as the Main Linac enclosure, a section of the Linac enclosure with an elevated (high) ceiling, a “ramp” which

connects the main Linac enclosure to the MTA “stub” elevationwise, an alcove section embedded in the primary shield wall which houses the beam stop (a critical device), the primary shield wall below the access hatch, and, finally, the part of the MTA beamline contained in a ~10'x 10' prefabricated concrete stub. The first three sections, from Z=0 to Z=103 (up to the shield wall) are either partially or entirely installed on a slightly inclined floor (about 1.5 degrees upward). Additionally there is a 2.5' step down from the MuCOOL beamline stub into the experimental hall. Table I gives the stationing of the six regions, in addition to three areas that are a part of the Experiment mode, relative to the defined start point at the upstream face of the 1<sup>st</sup> C magnet. The MuCOOL Radiation Safety Drawings, 9-4-1-35 C-2 and C-3, show the nine areas with the exception of the alcove and the beam absorber. The sections of the beamline which lie in the different longitudinal-shielding areas have been outlined in Attachment 2. Attachment 3 shows the details of the shield wall, including beam stop alcove and penetrations. Attachment 4 contains the full civil engineering drawings of the final beam absorber.

**Z=0-41' Main Linac Enclosure:** The MuCOOL beamline starts in the Linac enclosure at the upstream end of the first pulsed C magnet. This magnet kicks the beam about 3 degrees to the west, achieving separation from the 400 MeV transfer line at the downstream end of the 400 MeV electrostatic chopper. A 2<sup>nd</sup> pulsed C magnet just downstream of the Chopper enhances the separation, to allow MTA beam to be steered into a separate and distinct magnetic channel. Downstream of the 2<sup>nd</sup> C magnet, all elements are unique to the MTA beamline and independent of the Linac and the 400-MeV line.

**Z=41-55' Linac High Ceiling:** About 40' from the start of the beamline, the enclosure ceiling height increases with a corresponding decrease in longitudinal shielding as shown in the MuCOOL Radiation Safety Drawings.

**Z=55-103' Linac Ramp:** The next section represents the pre-existing Linac access ramp, which ends at the upstream face of the shield wall.

**Z=103-106' Alcove:** A 5' high, 4' wide, and 3' long alcove inset in the shield wall houses the downstream part of the MTA beam stop. This alcove begins at the upstream face of the shield wall, as shown in Attachment 3.

**Z=106-115' Hatch Shield Wall:** Details of the shield wall are given in Attachment 4 including penetrations.

**Z=115-147' Beamline Stub:** The ~10x 10' beam stub between the shield wall and the experimental hall. This stub ends with a 2.5' step down into the experimental hall.

Attachment 5 contains the longitudinal shielding spreadsheets for all six areas for the Emittance and Experiment modes. The sections from Z=0 to 103' are protected by interlocked detectors for both the

Emittance and Experiment modes. In the rest of the nine areas, the shielding meets or exceeds the radiological requirements for the stated beam conditions for both modes, as indicated in Attachment 5.

**Table 1:** The nine longitudinal shielding sections.

<b>Description</b>	<b>Stationing</b>	<b>Northing</b>	<b>Easting</b>
Start	0	99511.30274'	99617.141898'
Main Linac Enclosure	41.4'	99503.14412'	99596.90133'
Linac High Ceiling	54.7'	99494.50715	99585.16936
Linac Access Ramp	102.6'	99459.95440	99551.65122
Beamstop alcove	105.6'		
Shield Wall	114.6'	99451.36564	99543.27872
Beamline stub	146.9'	99428.21164	99520.70773
Experimental Hall	186.9'	99399.56864	99492.78594
Absorber beam pipe	193.4'		
Absorber	202.9'		

### ***Transverse Shielding Summary***

The areas remain defined as in the longitudinal shielding section. Attachment 6 contains the transverse shielding spreadsheets for the Emittance and the Experiment modes. The first three sections, Z=0-103', have transverse shielding radial distributions given in the MuCOOL Radiation Safety Drawings (sections B - D and F-G). The shield wall has transverse shielding distributions as shown in Attachment 3. Again, the first three sections (Z=0-103') are protected by interlocked detectors for both modes. The radial distribution of shielding along the beamline in the downstream areas and through the absorber is sufficient in all cases, as indicated in reference Attachment 6.

### ***Labyrinth and Penetration Summary and Calculations***

The penetrations and labyrinths for the MuCOOL facility are listed and described below. Either MARS or labyrinth and penetration calculations were used for this assessment. The penetrations and labyrinths are listed in order from upstream to downstream below.

Hatch Shield Wall: Three penetrations were established in the shield wall to accommodate two RF waveguides and one containing cables from the RF trench at the top of the berm into the beamline stub and eventually the experimental hall. Two additional penetrations through the shield wall were necessary for the 3.25" diameter beam pipe and cabling between the Linac enclosure and the downstream beamline. The shield wall engineering drawings in Attachment 3 contain cross sectional slices of these penetrations at different longitudinal positions.

Ceiling Vent: A 20" diameter penetration in the experimental wall ceiling provides a vent for gases to the top of the berm (see Attachment 8 for drawings of the experimental hall).

Gas Manifold Room: Three 3"-diameter, single-leg penetrations run from the experimental hall to the hydrogen gas manifold room.

Refrigerator Room Cryo Penetrations: Six straight penetrations, one 10", one 8", and four 4" diameter openings, run from the experimental hall to the refrigerator room. The penetrations and their contents are detailed in Attachment 7.

Refrigerator Room Utility Penetrations: Another set of eight 5" diameter penetrations from the experimental hall enter the refrigerator room at ceiling height.

Pit labyrinth: One personnel labyrinth opens into the pit and remains at the pit floor elevation.

Ventilation ducts: One supply, 14.3" in diameter and one return duct, 18.1" enter and exit at the top of the service building.

Stairway Labyrinth: The second personnel labyrinth leads from the experimental hall upstairs to the service building parking lot.

The first three penetrations exit into an assessment category 4 area enclosed by a 4' fence which is posted and locked during MuCOOL operation.

## **General**

Two penetrations from the Linac beam enclosure to the beamline stub contain cabling and a 3.25" beam pipe. The cables are fed through the shield wall and tightly packed with sandbags to eliminate any potential for prompt dose. The beam pipe is shielded by a beamstop at the upstream end of the shield wall. Exposure during access to the MuCOOL experimental hall or beamline stub from losses in the Linac has been calculated using MARS to be less than 0.01 mrem/pulse as shown in Figure 4. The area is protected by an interlocked detector during access to the experimental enclosure.

Given the large number of labyrinths and penetrations to consider for the MuCOOL experimental hall and beamline, identifying a unique worst-case loss scenario for each case and in both the Emittance and the Experiment mode would represent an extensive body of work. Instead, a mode-independent approach was taken where the worst-case loss location and condition were determined for each individual labyrinth and penetration geometry producing the largest prompt dose per pulse achievable at their respective exit. This high dose per pulse is then scaled to 600 pulses/hour or 60 pulses/hour to assess the Emittance and Experiment mode, respectively. If the dose rate exceeds the acceptable limit, then a specific MARS model is invoked.

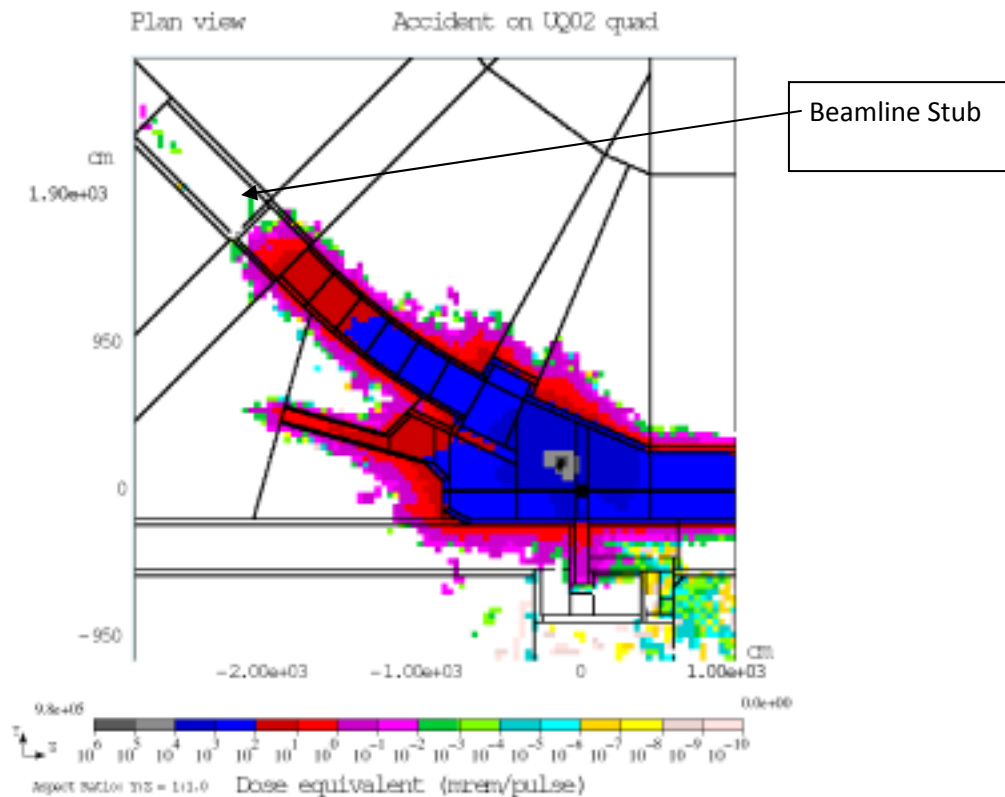


Figure 4. Prompt dose in experimental hall enclosure from worst-case loss in Linac for  $1.6 \times 10^{13}$  protons/pulse.

#### Emittance Mode:

**Hatch Shield Wall:** Two RF penetrations in the shield wall contain a 5" x 10" rectangular waveguide, and a 9" coaxial transmission line, both running from the top of the berm, through the hatch shielding, into the beamline stub. These RF penetrations were modeled using MARS for the worst case: losing the entire beam on a component about 7' downstream of the shield wall (Attachment 7 and Attachment 8, TM2457). The dose rate at the top of the berm is calculated to be 1.38 mrem/hr from the two RF waveguide penetrations combined. The Linac and MuCOOL berms are entirely enclosed by a 4' fence which is locked and posted during MuCOOL operation.

Cabling has been routed through the shield wall and tightly packed with sandbags to eliminate any potential for prompt dose.

**Ceiling Vent:** The voids in the 20" ceiling vent are filled with polyethylene beads. However, even with the beads, the dose rate from a beam loss downstream of the emittance absorber exceeds acceptable limits at 600 pulses/hour. Therefore a detailed MARS simulation was performed for the Emittance mode. Beam loss on the emittance absorber, which is the loss closest to the ceiling vent in the Emittance mode, plus a component with a smaller radial physical dimension, were modeled to determine the maximum possible dose rate. This MARS simulation, which is described in

Attachment 8, TM2457, indicates that the dose is less than 0.1 mrem/pulse, or 60 mrem/hr for beam lost on the emittance beam absorber. Beam loss on the emittance absorber was determined to represent the worst case due to location, since the emittance absorber is the component closest to the ceiling vent (for the Emittance mode), and since smaller transverse dimensions produced lower prompt dose (see Attachment 8).

Gas Manifold Room: The three penetrations to the gas manifold room are filled with polyethylene beads and cabling except for two 0.25" copper lines that feed gas to the experimental hall. Independent of the mode, the worst case for prompt dose in the gas manifold room is generated by a loss directly across from the penetrations as described in Attachment 8, TM2457. Such a loss delivers a combined dose of no more than  $1.51 \times 10^{-3}$  mrem/pulse in the gas manifold room. Therefore, the Emittance mode, where beam is deposited further upstream on the emittance absorber (at a rate of 600 pulses/hour), is, for worst case, 0.906 millirem/hour. This level is acceptable since the gas manifold room is inside a 4' fenced, posted area. The gas manifold room is protected by an interlocked detector.

Refrigerator Room Cryo Penetrations: A cage and a 2' shield wall in the refrigerator room surrounds and blocks the area around the exit of all six of these penetrations, preventing access by personnel. The MARS simulation gives the largest prompt dose at a point accessible by personnel to be  $1.51 \times 10^{-3}$  mrem/pulse (outside of the cage and downstream of the 2' shield wall ) based on the worst case described in Attachment 8, TM 2457, independent of mode. The worst case for beam lost on the emittance absorber, which is further upstream, is this value scaled to 600 pulses/hour, or  $9.06 \times 10^{-1}$  mrem/hour. The dose at the exit of the penetrations is monitored by an interlocked detector.

Refrigerator Room Utility Penetrations: The total dose from all eight utility penetrations in the refrigerator room , which are grouped together by geometry, was calculated using labyrinth spreadsheets, which is the standard methodology. This gives a summed dose of  $3.92 \times 10^{-15}$  mrem/pulse in the refrigerator room at the exit of the penetrations (Attachment 7). Beam deposited on the emittance absorber, which is further upstream and designed to stop forward-directed loss particles, is, at worst,  $2.35 \times 10^{-12}$  mrem/hour (for 600 pulses/hour).

Pit labyrinth: The pit is a posted radiation area. Using the standard methodology of labyrinth spreadsheets, the maximum prompt dose at the exit of the pit labyrinth door is calculated to be  $5.02 \times 10^{-4}$  mrem/pulse (Attachment 7). For 600 pulses/hour in the emittance mode, the prompt dose from beam deposited on the emittance absorber, which is much further upstream, is then, in the worst case,  $3.01 \times 10^{-01}$  mrem/hour at the pit labyrinth exit door.

Ventilation ducts: Using labyrinth spreadsheets, the supply vent on the roof of the service building delivers a prompt dose of  $9.32 \times 10^{-10}$  mrem/pulse (Attachment 7). The dose from beam deposited on the emittance absorber at 600 pulses/hour will therefore be, at worst,  $5.59 \times 10^{-7}$  mrem/hour. The maximum prompt dose delivered at the exit of the return vent is  $2.97 \times 10^{-9}$  mrem/pulse

(Attachment 7). The prompt dose from beam on the emittance absorber is, at worst,  $1.78 \times 10^{-6}$  mrem/hour for 600 pulses/hour.

Stairway Labyrinth: The worst-case dose at the labyrinth exit door leading outside (parking lot level) as calculated using labyrinth spreadsheets is  $1.10 \times 10^{-7}$  mrem/pulse (Attachment 7). For beam deposited on the emittance absorber at 600 pulses/hour, the dose is, at worst,  $6.60 \times 10^{-6}$  mrem/hour at the labyrinth exit door.

### ***Air Activation Calculations, Estimate of Annual Release, and Air Release Points***

Figure 5 shows the air intake and exhaust vents located at the top of the service building and experimental hall. The exhaust ducts for both the experimental hall and service buildings are then extended through piping into the tank farm area. The air activity released into the tank farm area as a function of air flow rate is given in Table 2.

The maximum EPA/IEPA allowable dose to a Maximally Exposed Offsite Individual (MEOI) from the Lab's air emissions is 100 micro-rem per year. The Fermilab Radiological Control Manual further limits exposure offsite to 10 mrem/year. At that level the laboratory is not required to provide EPA-approved continuous monitoring of all its emissions sources.

**Table 2:** The maximum number of protons/year to the MTA facility based on air flow rate.

Protons/year	FlowRate(cfm)
6.20E+20	50
3.21E+20	60
1.24E+20	80
6.49E+19	100
4.08E+19	120
2.86E+19	140
2.16E+19	160
1.72E+19	180
<b>1.48E+19</b>	<b>196</b>
1.43E+19	200
1.22E+19	220
7.69E+18	300
3.69E+18	600
2.76E+18	900
2.35E+18	1200

Based on a managed allotment for all emission sources at Fermilab, 30 Ci/year from the MuCOOL Facility was determined to be a reasonable addition. The maximum number of protons/year that may be delivered to the MTA Experimental Hall is therefore driven by air activation, which depends on the air

flow rate, or fan speed, as given in Table 2. For the MTA hall, the fan speed determined by ODH requirements is 1200 cfm, which corresponds to a maximum of  $2 \times 10^{18}$  protons per year.

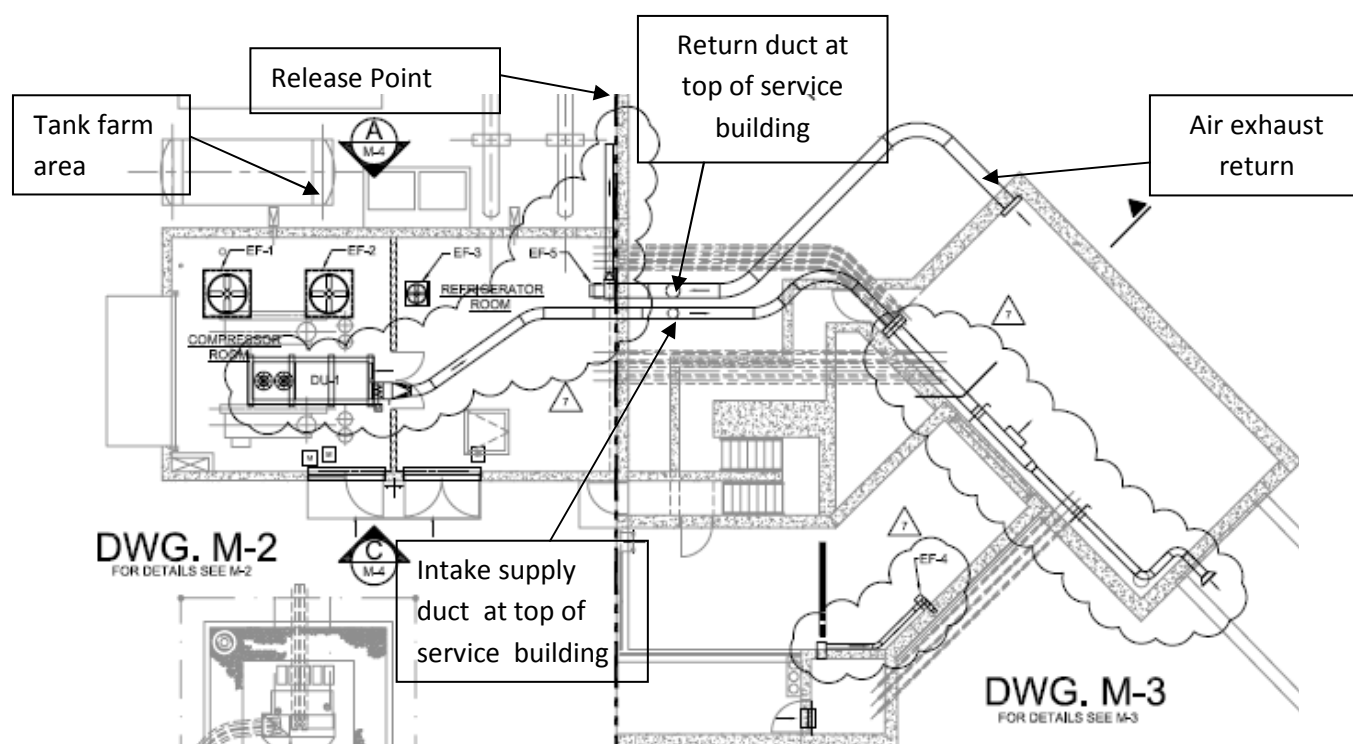


Figure 5. Air exhaust vent for the experimental hall and service buildings.

### ***Ground and Surface Water Activation Calculations and Surface Water Discharge Points and Monitoring Locations***

The estimates for ground and surface water are given in Attachment 9, for both the Emittance mode (Appendices 1 and 2 of Attachment 9) and the Experiment mode (Appendices 3 and 4). The limit for tritium,  $H^3$ , in surface water is 2000 pCi/ml and for sodium-22,  $Na^{22}$ , it is 10 pCi/ml. For ground water the tritium limit is 20 pCi/ml and for sodium-22, it is 0.4 pCi/ml.

The calculation of the star density associated with the emittance absorber is listed in the MARS compilation of Attachment 10, and the activation results are given in Attachment 9. The surface water activation limit would be reached if the emittance absorber were irradiated with  $2.9 \times 10^{20}$  protons/year, or about 2090 pulses per hour at full intensity. Activity generated by continuous beam in the emittance mode, at 600 pulses per hour, does not exceed this level, which is  $8.4 \times 10^{19}$  protons/year. The number of protons delivered to the MTA facility will be less than  $2 \times 10^{18}$  protons/year.

Beneath the experimental hall are drain tiles to collect surface water. A sump pump located in the northeast corner of the pit area collects surface water from around the experimental hall and discharges by way of the Booster sump system. The water is then sent to a discharge trench along Booster Road as shown in Figure 6. The beamline enclosure on the Linac side, upstream of the shield wall, is tied into this Booster sump system.

Booster sump concentrations are regularly sampled in Fermilab's routine monitoring program.

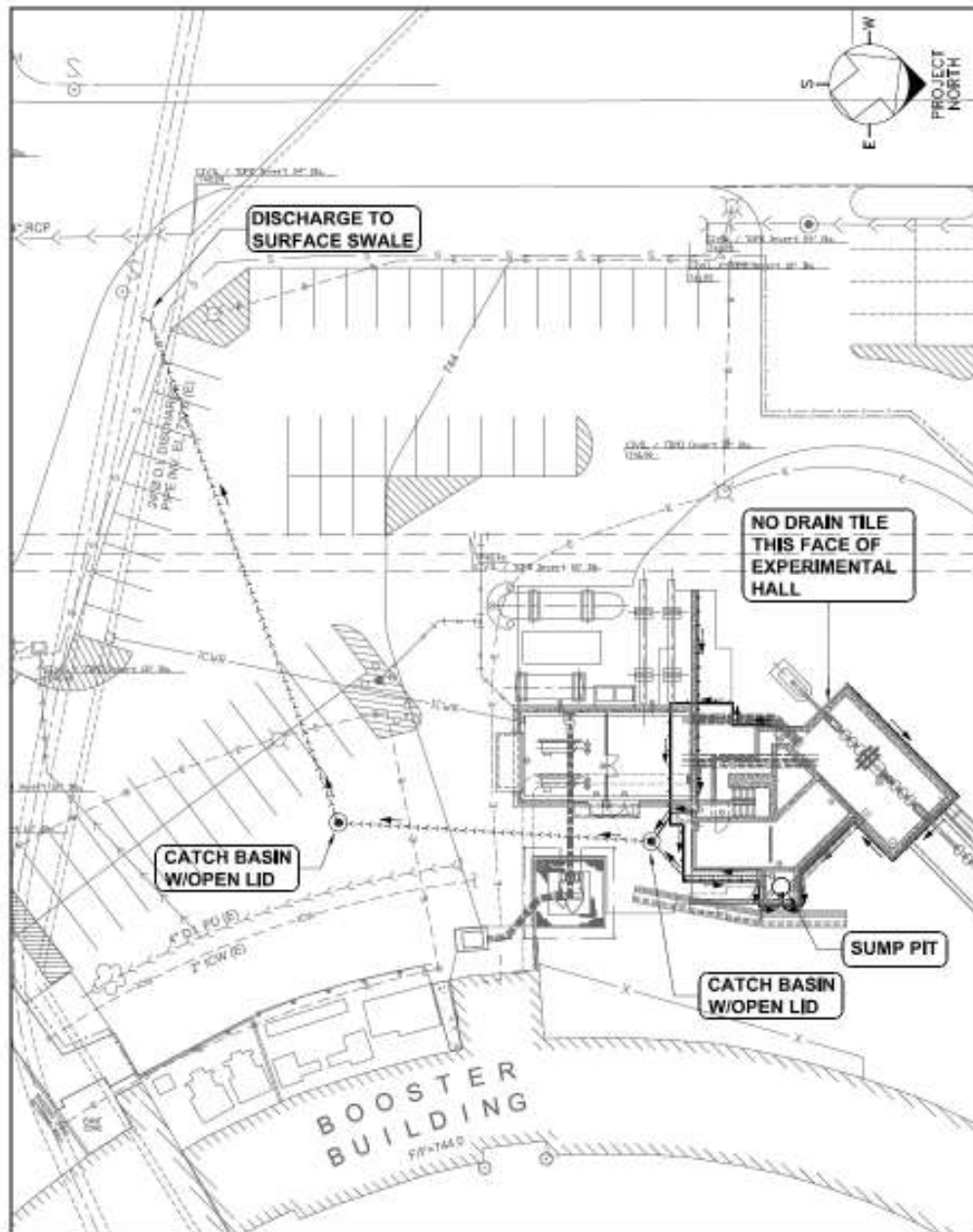


Figure 6. Surface water collection and discharge points.

## Muon Production

Muons are produced through pion decay, and the number of pions in the hadronic cascade increases with proton kinetic energy. Pion production becomes energetically possible only when the proton kinetic energy is higher than the rest mass of the pion, 139 MeV, as is just the case with 400-MeV protons. The maximum energy of the secondary muons is therefore less than 260 MeV. From Reference 2 the muon range at 300 MeV for graphite (1.700 g/cm<sup>2</sup>) and carbon (compact, 2.265 g/cm<sup>2</sup>) is 3' and 2', respectively. Since concrete and berm exceed the density of graphite, and more than 10' combined (1.5' and 9' of concrete enclosure and berm, respectively) exists in all directions per the MuCOOL Radiation Safety Drawings, there is adequate shielding in place to range out the muons.

## Residual Dose Rate Estimates

The residual dose rates on copper (Cu) and steel have been calculated for long and short (1 hour) beam periods. As shown in the Figure 7, the Emittance mode has been calculated for steel at 10 pulses/min. Potential residual activation hazards may be considerable and will be handled operationally as in all other Accelerator Division primary beam enclosures.

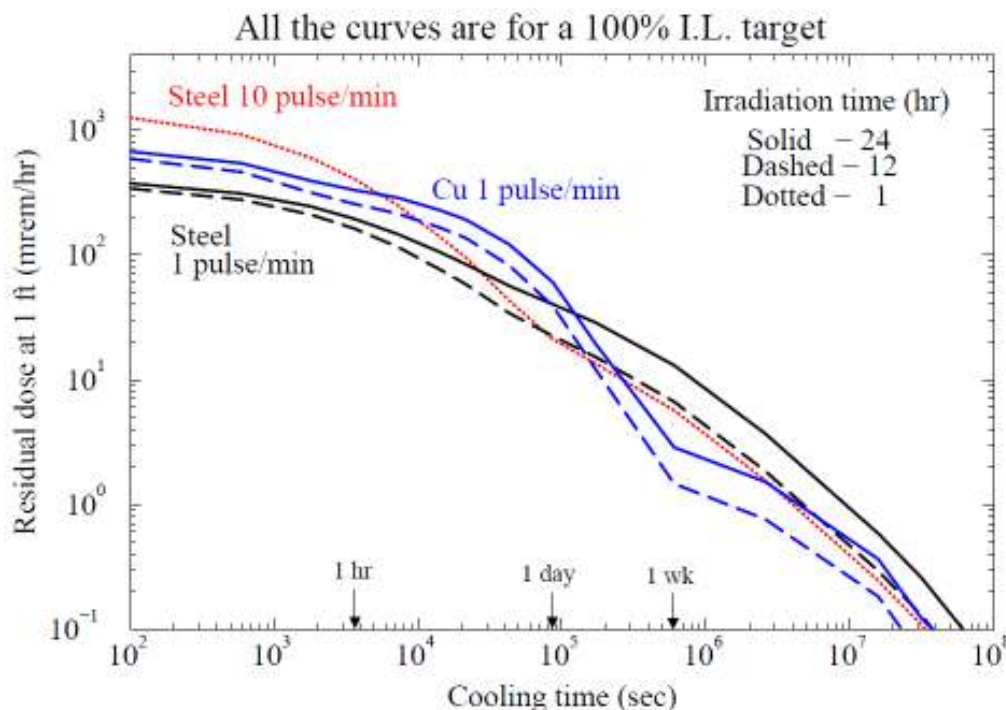


Figure 7. The calculated potential residual dose at one foot for Emittance and Experiment mode, and  $1.6 \times 10^{13}$  p/pulse, on 100% interaction length Cu and steel targets for 12, 24, and 1 hour periods of beam followed by a cooling period. A 100% interaction length target represents the worst case.

## ***Intended Active Shielding Controls and Monitoring***

An interlocked rate limiter actively counts Linac pulses delivered to the MuCOOL beamline. If the number of pulses allowed in Running Conditions is exceeded, beam is disabled through the critical devices. For the Emittance mode, the number is 600 pulses/hour. Attachment 11 is a description of the rate limiter.

Interlocked detectors in the Linac High Ceiling area and Linac ramp (Z=55-103') and also the hatch shield wall (Z=106-115') limit dose rates appropriate to the area postings as needed.

## ***EXPERIMENT MODE***

### ***Longitudinal Shielding Summary***

The longitudinal shielding part of the assessment crosses the six areas described previously under Emittance Mode Longitudinal Shielding, continuing through three additional areas downstream of the beamline stub. These are the 20' x 40' MTA experimental hall, the region occupied by a 6' long beam pipe that connects the MTA hall to the absorber, and the final beam absorber. Table I gives the stationing of all nine areas.

**Z=147-187 ' Experimental Hall:** A 20'x40' enclosure housing the experimental apparatus.

**Z=187-193 ' Beam pipe to Absorber:** A 6.5' long beam pipe is installed starting from the downstream wall of the experimental hall to upstream face of the beam absorber, Attachment 4.

**Z=193-203 ' Final beam absorber:** Engineering drawings are given in Attachment 4. Attachment 12 gives a full description of the absorber design and ANSYS calculations used.

Attachment 5 contains the longitudinal shielding spreadsheets for all nine areas for the Experiment mode. The sections from Z=0 to 103' are protected by interlocked detectors for both the Emittance and Experiment mode. In the rest of the nine areas, the shielding meets or exceeds the radiological requirements for the stated beam conditions for both modes.

### ***Transverse Shielding Summary***

The areas remain defined as in the longitudinal shielding section. Attachment 6 contains the transverse shielding spreadsheets for the Emittance (Attachment 6A) and the Experiment (6B) modes. The first three sections, Z=0-103', have transverse shielding radial distributions shown in the MuCOOL Radiation Safety Drawings (sections B - D and F-G). The shield wall has transverse shielding distributions as shown in Attachment 3. Again, the first three sections (Z=0-103') are protected by interlocked detectors for both modes. The radial distribution of shielding along the beamline in the downstream areas and through the absorber is sufficient in all cases, as indicated in reference Attachment 6 for the Experiment mode.

## ***Labyrinth and Penetration Summary and Calculations***

The penetrations and labyrinths for the MuCOOL facility were listed under this section for the Emittance mode. Either MARS or labyrinth and penetration calculations were used for this assessment (Attachment 7 and 8).

### **Experiment Mode:**

Hatch Shield Wall: Two RF penetrations in the shield wall contain a 5" x 10" rectangular waveguide, and a 9" coaxial transmission line, both running from the top of the berm, through the hatch shielding, into the beamline stub. These RF penetrations were modeled using MARS for the worst case: losing the entire beam on a component about 7' downstream of the shield wall (Attachment 7 and Attachment 8, TM2457). The dose rate at the top of the berm is calculated to be 0.138 mrem/hr from the two RF waveguide penetrations combined. The Linac and MuCOOL berms are entirely enclosed by a 4' fence which is locked and posted during MuCOOL operation.

Cabling has been routed through the shield wall and tightly packed with sandbags to eliminate any potential for prompt dose.

Ceiling Vent: With voids filled with polyethylene beads, the MARS simulation described in Attachment 8, TM2457 indicates that the dose is less than or equal to 0.3 mrem/pulse, or 6 mrem/hour for a beam loss nearest the ceiling vent (which represents the worst-case beam loss).

Gas Manifold Room: The three penetrations to the gas manifold room are filled with polyethylene beads and cabling except for 0.25" copper lines that feed gas to the experimental hall. The copper lines do not provide a direct path for neutrons. Independent of the mode, the worst case for prompt dose in the gas manifold room is generated by a loss directly across from the penetrations as described in Attachment 8, TM2457. Such a loss delivers a combined dose of no more than  $1.51 \times 10^{-3}$  mrem/pulse in the gas manifold room. For the Experiment mode, where beam is delivered at a rate of 60 pulses/hour, the worst case is 0.0906 millirem/hour. This level is acceptable since the gas manifold room is inside a 4' fenced, posted area. The gas manifold room is protected by an interlocked detector.

Refrigerator Room Cryo Penetrations: A cage and a 2' shield wall in the refrigerator room surrounds and blocks the area around the exit of all six of these penetrations, preventing access by personnel. The MARS simulation gives the largest prompt dose at a point accessible by personnel to be  $1.51 \times 10^{-3}$  mrem/pulse (outside of the cage and downstream of the 2' shield wall ) based on the worst case described in Attachment 8, TM 2457 independent of mode. The worst case beam loss, when this value scaled to 60 pulses/hour, is  $9.06 \times 10^{-2}$  mrem/hour. The dose at the exit of the penetrations is monitored by an interlocked detector.

Refrigerator Room Utility Penetrations: The total dose from all eight utility penetrations in the refrigerator room , which are grouped together by geometry, was calculated using labyrinth spreadsheets which is the standard methodology. This gives a summed dose of  $3.92 \times 10^{-15}$

mrem/pulse in the refrigerator room at the exit of the penetrations (Attachment 7). The worst case loss is  $2.35 \times 10^{-13}$  mrem/hour for 60 pulses/hour.

Pit labyrinth: Using the standard methodology of labyrinth spreadsheets, the maximum prompt dose at the exit of the pit labyrinth door is calculated to be  $5.02 \times 10^{-4}$  mrem/pulse (Attachment 7). For 60 pulses/hour in the Emittance mode, the prompt dose from beam deposited on the emittance absorber, which is much further upstream, is then, in the worst case,  $3.01 \times 10^{-02}$  mrem/hour at the pit labyrinth exit door.

Ventilation ducts: Using labyrinth spreadsheets, the supply vent on the roof of the service building delivers a prompt dose of  $9.32 \times 10^{-10}$  mrem/pulse (Attachment 7). The dose from beam deposited at 60 pulses/hour will be, at worst,  $5.59 \times 10^{-8}$  mrem/hour. The maximum prompt dose delivered at the exit of the return vent is  $2.97 \times 10^{-9}$  mrem/pulse (Attachment 7). The prompt dose is, at worst,  $1.78 \times 10^{-7}$  mrem/hour for 60 pulses/hour.

Stairway Labyrinth: The worst-case dose at the labyrinth exit door leading outside (parking lot level) as calculated using labyrinth spreadsheets is  $1.10 \times 10^{-7}$  mrem/pulse. For 60 pulses/hour, the dose is, at worst,  $6.60 \times 10^{-6}$  mrem/hour at the labyrinth exit door.

### ***Air Activation Calculations, Estimate of Annual Release, and Air Release Points***

The air activation and release estimates and points for the Experiment mode are discussed in the corresponding Emittance mode section above.

### ***Ground and Surface Water Activation Calculations and Surface Water Discharge Points and Monitoring Locations***

The estimates for surface water and ground water are given in Attachment 9 for the Experiment mode (Appendices 3 and 4). The limit for tritium,  $H^3$ , in surface water is 2000 pCi/ml and for sodium-22,  $Na^{22}$ , it is 10 pCi/ml. For ground water the tritium limit is 20 pCi/ml and for sodium-22, it is 0.4 pCi/ml. Both the description and the calculation of the star density associated with the final beam absorber are given in Attachment 12.

Surface water concentrations will need to be evaluated in detail for any particular configuration of experimental apparatus. An example of a "thick" experiment which may be typical was studied. A high-pressure RF cavity followed by an absorber, not enclosed in the MTA solenoid magnet, would reach the surface water activity limit at  $6.7 \times 10^{20}$  protons per year, or about 4780 pulses per hour at full intensity. Activity generated by continuous beam in the Experiment mode, at 60 pulses per hour, would not exceed this level ( $0.84 \times 10^{19}$  protons/year). The number of protons is anticipated to be significantly less than  $10^{19}$  protons/year.

This calculation is intended only to offer a typical example; any new experiment must be analyzed separately. This includes "thin" apparatus, where a substantial fraction of the incident beam does not interact.

Beneath the experimental hall are drain tiles to collect surface water. A sump pump located in the northeast corner of the pit area collects surface water from around the experimental hall and discharges by way of the Booster sump system. The water is then sent to a discharge trench along Booster Road as shown in Figure 6. The beamline enclosure on the Linac side, upstream of the shield wall, is tied into the Booster sump system.

Booster sump concentrations are regularly sampled in Fermilab's routine monitoring program.

Beam transported to the final absorber, buried in the berm beyond the downstream wall of the MTA enclosure, is designed to absorb high intensities.

There was no granular underdrainage installed in this region. Instead water percolates into the soil around and below the absorber. Therefore surface water limits are not relevant.

Groundwater limits would be reached with  $2.01 \times 10^{20}$  protons per year incident on the final absorber, or about 1430 pulses per hour in continuous operation at full Linac intensity (Attachments 9 and 13).

Activity generated by continuous beam in the Experiment mode, at 60 pulses per hour, would therefore not exceed this level.

## ***Muon Production***

The background considerations for muon production, the threshold, maximum, and range energy of secondary muons, are discussed in the Emittance mode section and apply to the Experiment mode as well.

As in the Emittance mode, since concrete and berm exceed the density of graphite and more than 10' combined (1.5' and 9' of concrete enclosure and berm, respectively) exists in all directions per MuCOOL Radiation Safety Drawings, the shielding in place is more than needed to range out the muons at all locations in the experiment hall.

The following is a general example where neutron and muon fluxes were calculated for a gas-filled RF test cell located in the experimental hall along with an energy spectrum of the generated muons, Figure 8. The average energy of the muons is 15 MeV and, as shown in Figure 9, muons lose all their energy in the concrete walls of the enclosure. Muon production and flux calculations are required and must be addressed in each experimental assessment.

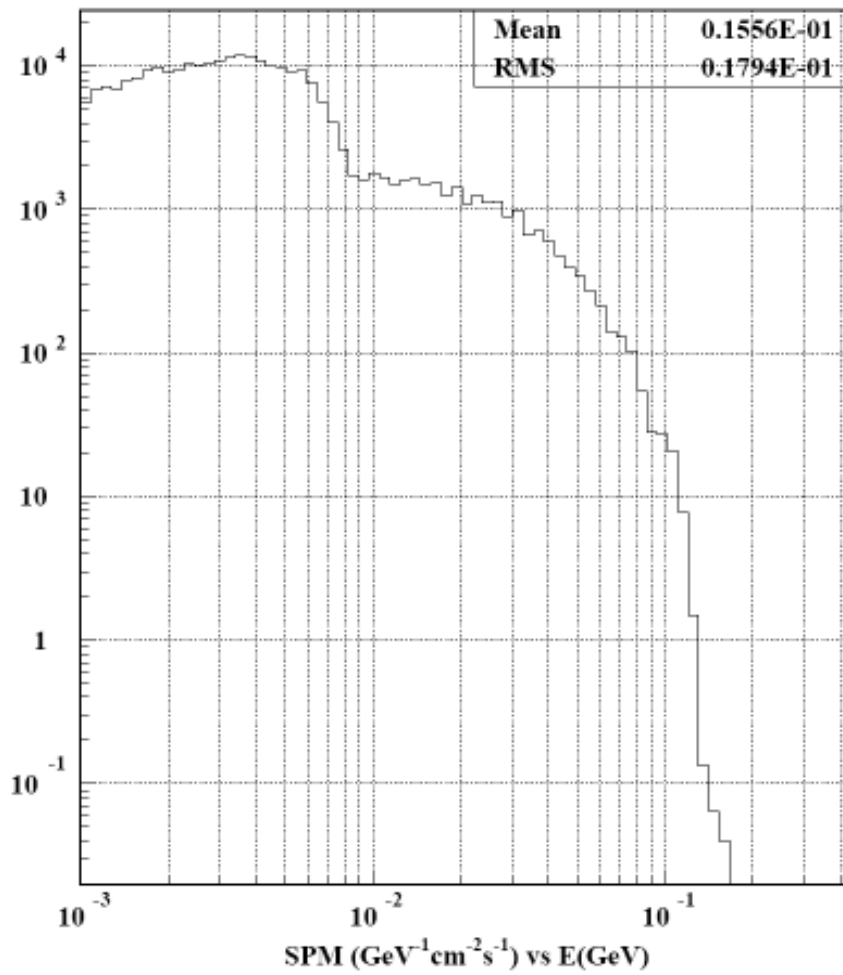


Figure 8. Muon energy spectrum from 400-MeV protons incident on a gas-filled RF test cell in the experimental hall for  $1.6 \times 10^{13}$  p/pulse and 1 pulse/minute (Experiment mode). The flux for the Emittance mode is a factor of 10 higher.

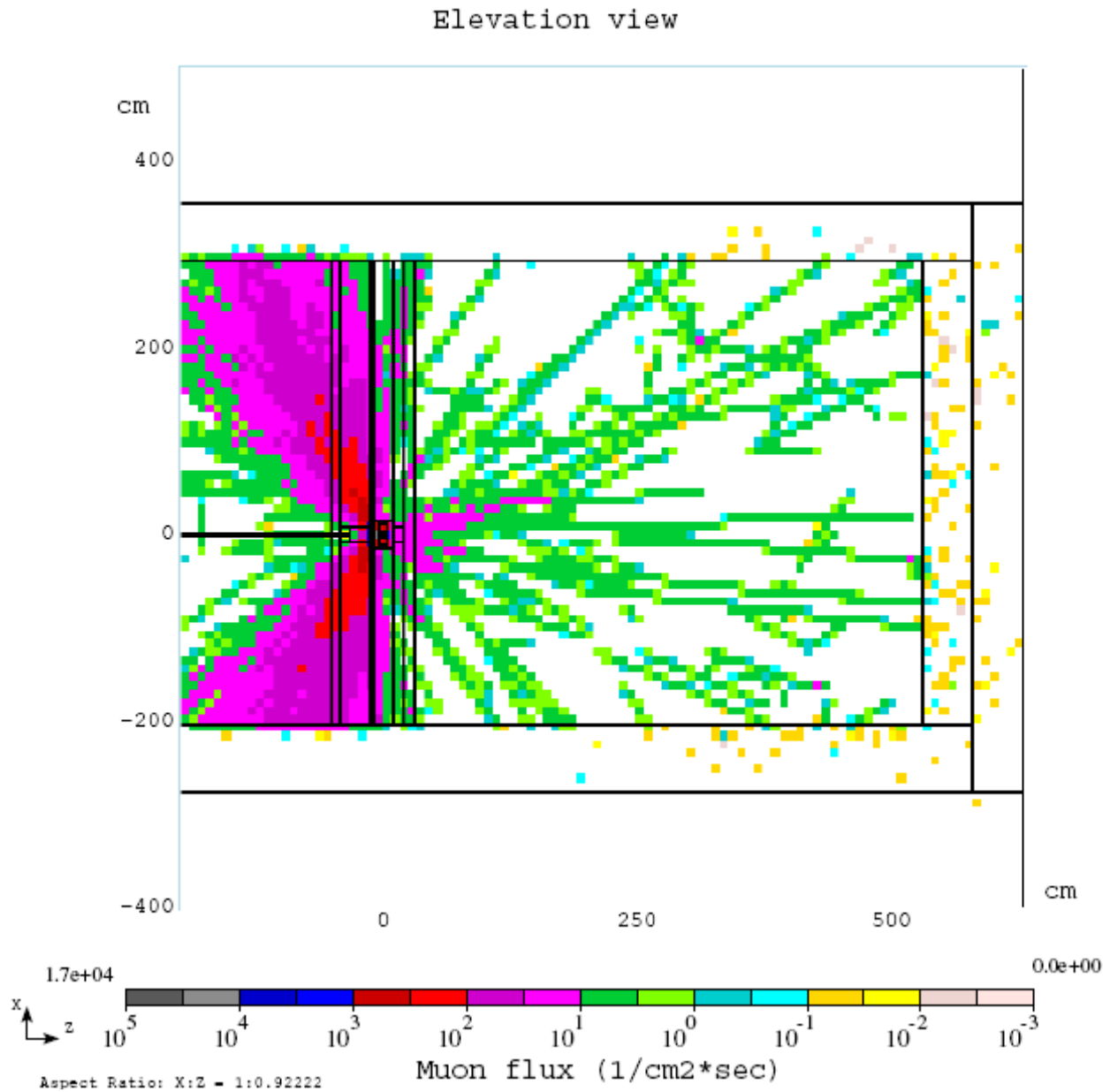


Figure 9. Muon flux in the experimental hall for  $1.6 \times 10^{13}$  p/pulse and 1 pulse/minute (Experiment mode) on a gas-filled RF test cell with thick (>100% Interaction length) walls. The flux for the Emittance mode is a factor of 10 higher.

### ***Residual Dose Rate Estimates***

The residual dose rates on copper and steel have been calculated for long and short (1 hour) beam periods as shown in the Figure 7 for the Experiment mode (1 pulse/min). Potential residual activation

hazards, as in the Emittance mode, may be considerable and will be handled operationally, as in all other Accelerator Division primary beam enclosures.

### ***Intended Active Shielding Controls and Monitoring***

An interlocked rate limiter actively counts Linac pulses delivered to the MuCOOL beamline. If the number of pulses allowed in Running Conditions is exceeded, beam is disabled through the critical devices. For the Experiment mode, the number is 60 pulses/hour. Attachment 11 is a description of the rate limiter.

Interlocked detectors in the Linac High Ceiling area and Linac ramp (Z=55-103') and also the hatch shield wall (Z=106-115') will limit dose rates appropriate to the area postings as needed.

### ***References***

- [1] Ankenbrandt, C. et al, "Design report: Linac Experimental Area," FERMILAB-PUB-95-078 (Mar 1995).
  - [2] Groom, Donald E.; Mokhov, Nikolai V.; Striganov, Sergei, "Muon Stopping Power and Range Tables 10 MeV-100 TeV".
- <[http://www.physics.princeton.edu/~mcdonald/examples/detectors/groom\\_adnat\\_78\\_183\\_01.pdf](http://www.physics.princeton.edu/~mcdonald/examples/detectors/groom_adnat_78_183_01.pdf)>

### ***Attachments***

- 1) MuCOOL Shielding Requirements
  - 1A) Emittance Mode
  - 1B) Experiment Mode
- 2) The MuCOOL Beamline
- 3) MuCOOL Hatch Shielding Complete Assembly, 2130.000-ME-391334
- 4) MTA Absorber Installation Drawings, 4-1-35A
- 5) MuCOOL Muon Test Area Longitudinal Shielding
  - 5A) Emittance Mode
  - 5B) Experiment Mode
- 6) MuCOOL Transverse Shielding
  - 5A) Emittance Mode
  - 5B) Experiment Mode
- 7) Summary of Labyrinths and Penetrations in the Muon Test Area (MTA) Enclosure
- 8) TM-2457: Beam Loss Scenarios fo MuCOOL Test Area
- 9) Groundwater and Surface Water Activity in MuCOOL Beam Operations
- 10) The Emittance Absorber for the MuCOOL Beamline
- 11) MuCOOL Rep Rate Monitor Interlocks
- 12) MuCOOL Test Facility Beam Absorber
- 13) Surface and Groundwater Assessment of the MuCOOL Beam Absorber